GRIN: Final Report

EVALUATING THE POST-FIRE HYDROLOGIC RESPONSE IN SNOW DOMINATED CATCHMENTS IN COLORADO'S SAN JUAN MOUNTAINS

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List of Abbreviations/Acronyms

- **AET** - Actual evapotranspiration
- **CDWR** - Colorado Division of Water Resources
- **COM** - Center of mass
- **EF** - Evaporative fraction
- **ET** - Evapotranspiration
- **Hermosa-system**: Junction Creek (control) & Hermosa Creek (burn)
- **LAI** - Leaf area index
- **LS-system:** S-Creek (control) & LS-Creek (burn)
- **MODIS** - Moderate Resolution Imaging Spectroradiometer
- **MWBM** - Monthly Water Balance Model
- **NLCD** - National Land Cover Database
- **P** - Precipitation
- **PC** - Paired catchment(s)
- **PET** - Potential evapotranspiration
- **PRISM** - Parameter-elevation Regressions on Independent Slopes Model
- **RO** - Runoff
- **SSEBop** - Operational Simplified Surface Energy Balance
- **Trout-system:** Red Mtn. Creek (control) & Trout Creek (burn)
- **USFS** - U.S. Forest Service
- **USGS** - U.S. Geological Survey
- **WFC** - West Fork Complex

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Abstract

This study evaluates the hydrologic response of three snow dominated paired catchment systems to wildfire and co-occurring insect induced forest mortality. Study catchments are located in Colorado's San Juan Mountains, in the West Fork Complex Fire (2013) burn scar and 416 Fire (2018) burn scar. A combination of field observations, reanalysis and remote sensing products are used to evaluate the surface water budget, and inform predictive models, in response to disturbance. We found that the impact of fire alone was likely not great enough to produce runoff increases in burned basins, but that the combined impact of fire and insect mortality may alter

evapotranspiration enough to tip the scale toward increased post-fire runoff generation. These findings are limited to a small study area, but highlight the importance of considering co-occurring disturbances, especially with respect to wildfire-prone regions that are typically impacted by other forest mortalities.

1. Objectives

The originally proposed objectives of this study align most closely with the "**fire effects and post-fire recovery**" JFSP FON topic area (*italicized* below):

Objective 1: *First, we will evaluate surface water budget components during the post-fire recovery process of three snow-dominated paired catchments in Colorado's San Juan Mountains. We will use both ground-truth techniques and remotely sensed products to close surface water budgets in three paired catchments that each consist of a burned and control catchment. This study will look at immediate post-fire effects but will mostly focus on longer-term recovery (3+ years) following burn.*

> The majority of this report focuses on the water budget analyses proposed in Objective 1, which serves as the foundation of this work. We hypothesized that the wildfire disturbance would alter the hydrologic response in burned basins, relative to their respective control basins. Hydrologic discrepancies between burned and control basins were expected to be greatest in the first 1-3 post-fire years, and to become smaller over time (4+ years post-fire) as the landscape recovered. Specifically, we expected to see a decrease in annual evapotranspiration (due to destruction of vegetation) and consequently, and an increase in the magnitude of annual surface runoff. Additionally, we hypothesized that annual snowmelt runoff would occur earlier in burned basins, relative to control basins, due to reduced infiltration and altered pathways in post-fire systems.

Objective 2*: Second, a monthly water balance model will be applied at the study sites and dynamic parameters developed that represent the post-fire recovery process. Through development of dynamic parameters that represent changing physical watershed characteristics, our intention is to improve the skill of the U.S. Geological Survey's (USGS) Monthly Water Balance Model (MWBM) in post-fire applications.*

> Progression toward the completion of Objective 2 is ongoing. We originally proposed to develop a dynamic parameterization method using post-fire hydrologic observations from the West Fork Complex Fire (burned 2013), and to test that methodology using catchments from the 416 Fire (burned 2018). Resources required to proceed with model parameterization, calibration and validation have been obtained. However, because the hydrologic response to wildfire was variable across study basins (see Results and Discussion), and due to uncertainties that have arisen in calibration datasets (namely surface runoff in 416 basins), we are working on alternative approaches to the originally proposed second objective.
>
> Specifically, since surface runoff (streamflow) data collected at the 416 sites may not be adequate for use in model calibration, evaluation of an alternative burned site may be necessary to test modelling methodology. We are also considering an alternative calibration approach, where, instead of calibrating exclusively to surface runoff, a two-step calibration approach (calibrating to both surface runoff and evapotranspiration) would be employed. Recent literature has shown that the inclusion of a second calibration step, where selected model parameters are calibrated against evapotranspiration, can enhance the skill of the model in question (Dile et al., 2020, Schneider & Hogue, *in prep*).

***Objective 3**: Finally, we will use the MWBM to generate synthetic streamflow scenarios that represent a range of future climate possibilities as the burned watersheds continue to recover. Water managers often rely on "scenario planning" to make decisions for future water governance.*

Progression toward the completion of Objective 3 is also ongoing, and ultimately depends on the completion of the modelling methodology outlined in Objective 2. Recent discussions with the Rio Grande Basin Round Table have highlighted their need to evaluate the water yield for the greater Rio Grande Headwaters under future climate and land-disturbance scenarios. In support of those needs and the Rio Grande Basin Implementation Plan Update, we plan to expand our originally proposed streamflow scenarios to the entire Rio Grande Headwaters area. All objectives outlined here also contribute significantly to the student investigators PhD dissertation work and are anticipated to be completed by fall of 2021.

2. Background

In the arid western U.S. water supply often falls short of water demand. In the case of the Rio Grande River basin, water yield distribution is governed by the Rio Grande Compact of 1938 (Rio Grande Compact, 1938) and must be divvied up between all downstream water-right holders, including those in Colorado, New Mexico and Texas. The snowy headwaters of the Rio Grande supply most of the water yield to downstream users. In Colorado alone, Rio Grande water is shared among municipal, agricultural, industrial and in-stream water rights holders. Thus, characterization of hydrology and hydrologic disturbances in the Rio Grande headwaters, as well as predictive tools that appropriately represent the dynamic hydrologic environment, are necessary for water managers to plan for current and future water needs.

Since the 1980s, wildfires have been increasing in duration and frequency in the western U.S. These increases are especially pronounced in mid-elevation, snow-dominated forests, where earlier spring snowmelt enhances vulnerability to fire frequency (Westerling, 2006). Wildfires act as extreme disturbances to hydrologic systems, threaten water quality (Rust et al., 2019) and alter water yield (Saxe et al., 2018). Beyond water yield, wildfires have also been shown to alter soil moisture content (Ebel, 2013), snow albedo and melt (Gleason et al., 2013, Gleason et al., 2019) and evapotranspiration (ET) due to destruction of vegetation. However, the compounded impact of each of these signals is often variable at the stream outlet (Goeking & Tarboton, 2020), especially in the southern Rocky Mountains (Saxe et al., 2018).

The amount of water available to runoff (as streamflow) is based on the difference between precipitation and ET. When vegetation is destroyed, less rain or snow is intercepted by the canopy (where it would otherwise quickly evaporate or sublimate) and the vegetative demand for water is reduced. Thus, with decreases in evapotranspiration, it is logical to expect an increase in streamflow. Also, post-disturbance seasonal streamflow in snow-dominated systems is often predicted to occur *earlier*, due to faster snowmelt caused by reduced canopy shading of on-ground snow.

However, a recent review on the disturbance effects on streamflow in the western U.S. reveals substantial disagreement in the literature (Goeking & Tarboton, 2020). Goeking and Tarboton (2020) find that streamflow response to vegetation destruction is variable in the Western U.S. Specifically, they find that after stand-replacing disturbances (severe wildfire, harvest) streamflow is more-likely to increase, but after nonstand-replacing disturbances (low-severity wildfire, insects, drought) streamflow is much more variable and may increase, decrease or experience no change. Their review highlights the need for additional studies to better understand post-disturbance hydrology, and for better representation of forest disturbances in hydrologic models through the incorporation of *quantitative* vegetation characterization.

With respect to wildfire, the extent of burn severity (stand-replacing vs nonstand-replacing) can vary widely within a drainage. And often, the wildfire event is a consequence of pre-existing disturbance(s), like insect-induced tree mortality and/or drought, which prime the forest for burn (Parker et al., 2006). The extent and heterogeneity of burn severity, as well as the presence of co-occurring disturbances, likely influence post-fire hydrologic behavior, and may contribute to the apparent variability in post-fire streamflow across semiarid western watersheds. Here, we present a water budget case study of burned semiarid and snow-dominated catchments in Colorado's San Juan Mountains (Objective 1), that are characterized by heterogeneous burn severities and co-occurring insect-induced tree mortality. This water budget analysis sets the stage for future work in the same area, where Leaf Area Index will be integrated into a water balance model to quantitatively represent forest-disturbance within the model (Objective 2) and to evaluate future forest-disturbance scenarios (Objective 3).

3. Materials & Methods

3.1 Study Area

To assess the hydrologic impacts of wildfire in the San Juan Mountains, three paired catchment (PC) systems located in two burned areas are evaluated for changes in surface water budget components. The burned areas include those from the West Fork Complex (WFC) Fire (2013) and the 416 Fire (2018). Two PC systems are located in the WFC burn scar and one PC system is located in the 416 burn scar; where each PC system contains one burned basin located adjacent to an unburned (control) basin. **Figure 1** and **Table 1** summarize the location and relevant geophysical parameters associated with each study basin. Study basins in the WFC Fire area are tributary to the main stem of the Rio Grande River, along its headwaters. Study basins in the 416 Fire area are tributary to the Animas River near Durango, Colorado. Before their respective fire events, WFC basins were dominated by evergreen forests and grassland/herbaceous vegetation and 416 basins were dominated by evergreen and deciduous forests (MRLC, 2011, MRLC, 2016). All study basins are located in Colorado's San Juan Mountains and receive the majority of annual precipitation as winter snow that accumulates during cold months and melts during warmer and dryer months.

For the study of hydrologic disturbance, the PC system approach inherently assumes that the only major difference between the impacted (burned) and control basins is the disturbance in question; in this case, wildfire. Specifically, it is assumed that basins within each PC system experience the same (or extremely similar) climate, that geologies are similar, and that forest cover and type (prior to the disturbance) is similar. Basins within each PC system have similar elevation profiles, and approximately the same slope aspect, so we assume that minor discrepancies between elevation and slope aspect will not significantly alter the hydrologic behavior of the burned basin relative to its control basin. We also assume that if PC systems are experiencing any other type of environmental disturbance, that each basin is similarly impacted by that disturbance.

Here, all basins were severely impacted by beetle kill prior to each burn event (BAER, 2013, USFS Forest Health Protection, 2005 - 2017). Since the forest impact from insects is similar across all study basins (**Table 1**), the hydrologic influence on control and burned basins should also be similar. However, the ongoing forest recovery from insect mortality may cause the control basins to behave differently (hydrologically) than a totally healthy forested basin.

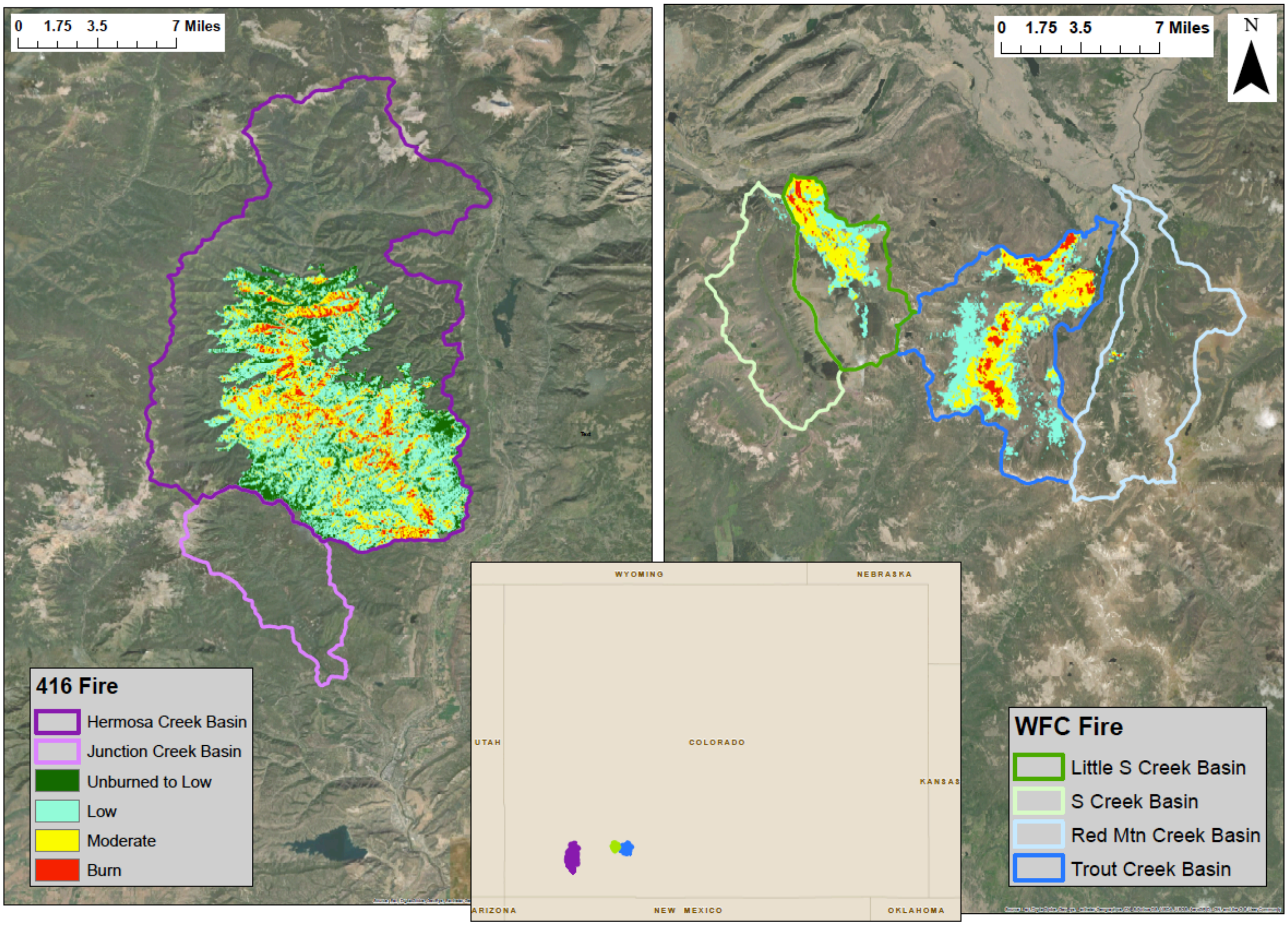

Figure 1: Study Area Map (above)

Table 1: Geophysical Parameters for Study Basins (below)

Burn Scar	Basin I = Impact C = Control	Elevation Range (Minimum – Maximum) [m]	Area [km^2]	Area Burned [%]	Area of Moderate and Severe Burn [%]	Area impacted by insects prior to fire [%]
West Fork Complex Fire [3013]	Trout Creek (I)	2,708 – 3,883	101	42	21	76
	Red Mtn. Creek (C)	2,700 – 4,003	83	1	0	64
	Little-S Creek* (I)	2,835 – 3,967	47	37	20	60
	S-Creek* (C)	2,846 – 3,968	56	1	0	59
416 Fire [2018]	Hermosa Creek (I)	2,149 – 3,879	436	35	13	54
	Junction Creek (C)	2,044 – 3,830	66	0	0	43

**Note: Little-S and S-Creeks can be respectively identified on a map as "Little Squaw Creek" and "Squaw Creek", but are referred to in this paper by the former naming convention.*

3.2 Data sources

Geophysical information

Burn severity rasters (30 meter resolution) detailing low, moderate and high burn severity were sourced from the US Forest Service (USFS). Shapefiles detailing forest impacts from insects were provided by the USFS Arial Detection Survey, and are based on annual aerial imagery from 2005 to the year before fire (2012 for WFC and 2017 for 416) (USFS Forest Health Protection, 2005-2017). Elevation information was taken from 1/3 arc-second USGS digital elevation maps (USGS, 2013).

Streamflow

First a note on terminology: in this report, "streamflow" and "discharge" are used interchangeably to describe streamflow as volume/time (ie: ft^3/s). The terms "runoff depth" and "surface runoff" refer to streamflow normalized by basin area, in depth/time (i.e.: mm/year).

Streamflow during post-fire years was sourced from a novel combination of observed (*in-situ*) and empirically derived discharge developed specifically for this study (described in greater detail below). In-situ streamflow was monitored in each stream using stilling wells outfitted with pressure transducers (Hobo Water Level Loggers) that recorded pressure at 15-minute intervals. Pressure transducers were deployed in stilling wells during the snowmelt season; approximately April/May through October for all post fire years through 2020. Next to each in-stream site, a Hobo logger was placed on land to correct water pressure recordings for local air pressure. During each annual melt season, stilling wells were visited on a monthly basis to manually measure discharge and water levels. Manual discharge measurements were taken following the USGS electromagnetic sensor method (Buchanan & Somers, 1969). Recorded pressure levels were correlated to manual measurements of discharge and water level to build rating curves for each site (see **Table 2** for rating curve R^2s).

In-situ streamflow measurements were occasionally disrupted by sedimentation inside stilling wells, animal activity, transducer malfunction, etc. During such disruptions, in-situ streamflow data was discarded, leaving (in some years) a severely abbreviated observational streamflow record. To fill in these streamflow "gaps" we developed empirically derived streamflow, relating discharge in study tributaries to discharge in the main stem of their receiving river (Rio Grande River for WFC sites, and Animas River for 416 sites). Power curve models of daily discharge were developed for each tributary; where tributary discharge was modeled as a dependent variable of discharge in the receiving river (independent).

Study basins in the WFC area are tributary to the Rio Grande River just below the Rio Grande Reservoir. To effectively remove the artificial reservoir contribution to discharge in the Rio Grande, we took the difference in Rio Grande discharge from 1) the outlet of the Rio Grande Reservoir and 2) another gage located 40 miles downstream (Colorado Division of Water Resource gages 2002127 and 2002128, respectively) (CDWR, 2021). Since the 40 stream-mile window between those two points captures exclusively tributary flow, we assume that this "Rio Difference" adequately represents the natural tributary contribution to the Rio Grande River, and use the Rio Difference as the independent variable in power-curve models used for empirical flow. Final continuous streamflow time series are composed of observational flow and empirical flow (where observational flow is absent), and exclude the months of November through March, when gages are often frozen. **Table 2** summarizes the goodness-of-fit of empirical flow relative to observed flow.

Table 2: Goodness-of fit-metrics for in-situ rating curves and empirically derived streamflow

Basin	Lowest R^2 from Rating Curves developed with in-situ measurements	Empirically Derived Flow vs. Observed Flow	
		NSE	Percent Bias [%]
Trout Creek	0.96	0.92	2.5
Red Mtn. Creek	0.92	0.90	-0.4
Little-S Creek	0.94	0.90	-4.0
S-Creek	0.95	0.81	-0.3
Hermosa Creek	0.88	0.55	11.4
Junction Creek	0.91	0.71	4.8

Climatic Data

Total monthly precipitation and average monthly temperature was sourced from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) at 4-km resolution (PRISM, 2020). Daily actual evapotranspiration (AET) was taken from the Operational Simplified Surface Energy Balance (SSEBop) product, at 1-km resolution (Senay & Kagone, 2019). Monthly potential evapotranspiration (PET) was estimated following the Hamon approach (Hamon, 1961, McCabe & Markstrom, 2007). All gridded climate products were aggregated to study basin polygons using a weighted extraction.

Leaf Area Index

A 4-day Leaf Area Index (LAI) product was sourced from the Moderate Resolution Imaging Spectroradiometer (MODIS) MCD15A3H Version 6, Level 4, at 500-m resolution (Myneni et al., 2015). A cloud correcting filter was applied to LAI, removing observations where significant cloud cover was present in study basins with 50% or greater coverage. Resulting 4-day cloud-filtered LAI observations were spatially aggregated to study basins and temporally aggregated to mean monthly LAI.

3.3 Water Budget Analysis

To determine the hydrologic response to wildfire, a surface water budget analysis was performed for all paired catchment systems, during post-fire years (Objective 1). The surface water budget is calculated as:

Storage Change (snow & subsurface) = Precipitation – evapotranspiration – surface runoff ± error

This report evaluates changes in post-fire runoff and evaporation (relative to precipitation) to better understand fire-induced changes in the hydrologic system. Although the PC approach to water budget analysis assumes that paired basins are similarly influenced by weather events (especially the timing of seasonal weather) additional steps must be taken to normalize water budget outputs against precipitation, to achieve best comparative results between burned and control catchments. We compute annual runoff ratios (total annual runoff depth divided by total annual precipitation depth) and evaluate residual trends taken from the linear relationship between total annual discharge and total annual precipitation. Residual trends are employed to quantify how much annual discharge is explained by annual precipitation.

To evaluate the timing of seasonal streamflow, annual flow mass is segmented into quartiles; identifying the dates when 25%, 50% and 75% of annual discharge occurred. More commonly referred to as the “center of mass” or “center of volume”, this approach reveals the timing of annual runoff while muting the influence of seasonal rainstorms that can cause peak annual discharge to occur earlier or later than it otherwise would. Center of mass calculations were carried out using statistical computing software R (R-Core-Team, 2021) and specifically, the ‘*FlowScreen*’ package (R-Core-Team, 2021).

Similar to runoff ratios, evaporative fractions (total annual ET divided by total annual precipitation) were computed to evaluate ET relative to precipitation.

3.4 Leaf Area Index Analysis

Leaf area index was selected as the land cover metric to incorporate into model dynamic parameterization (Objective 2). To determine whether or not MODIS based LAI adequately captures the land cover changes in burned catchments relative to their controls, we conducted change point analyses on “LAI residuals” for each paired catchment system ($LAI_{residual} = LAI_{control} - LAI_{burn}$), using the ‘*changepoint*' R package (Killick et al., 2016). Monthly LAI residuals were ultimately produced for the period of July 2002 through October 2020, based on the available period of record for MODIS LAI.

4. Results and Discussion

4.1 Runoff Analysis

Due to the lag in timing of annual snowfall and snowmelt, runoff results are presented in annual timesteps and are computed by summing daily runoff values for each water year (October – September). Recall that flow timeseries include a combination of observed and empirical data points. Due to equipment failures in Hermosa Creek caused by extremely high flows in the 2019 water year, we have the least amount of confidence in 2019 flow data for Hermosa Creek, which is likely under representative of true streamflow. For this reason, and because the 416 PC system only has 2 post-fire years, the majority of the discussion focuses on more robust results from the West Fork Complex catchments.

For ease of discussion PC systems are referred to by the name of the burned catchment, for example: the LS-Creek and S-Creek system is referred to as “LS-system”, the Trout Creek and Red Mtn Creek system is referred to as “Trout-system”, and the Hermosa Creek and Junction-Creek system is referred to as “Hermosa-system”.

4.1.1 RO Ratios

Annual runoff ratios [RO/P] were computed for post-fire water years in each PC system. Runoff ratios normalize annual runoff against annual precipitation to reveal the fraction of precipitation that becomes runoff. In the LS-system, runoff ratios in the burned basin are consistently *lower-than* or equal-to runoff ratios in the burned basin (**Figure 2-A**). Contrary to this, in the Trout-system, runoff ratios in the burned basin are consistently *higher-than* or equal-to those in the burned basin (**Figure 2-B**). In the two post-fire years of the Hermosa-system, runoff ratios vary between the control and burned systems (**Figure 2-C**).

We hypothesized that the greatest differences between burn and control catchments would occur in the first 1-3 post-fire years. However, none of the PCs that we evaluated behaved this way. Especially in the West Fork Complex PCs, runoff behavior in the first three post-fire years (2014-2016) is *not* notably different from runoff during the following years (2017-2020). We also hypothesized that the fraction of precipitation that becomes runoff would be higher in burned catchments. Of the three PC systems we evaluated, the Trout-system is the only one that behaved this way.

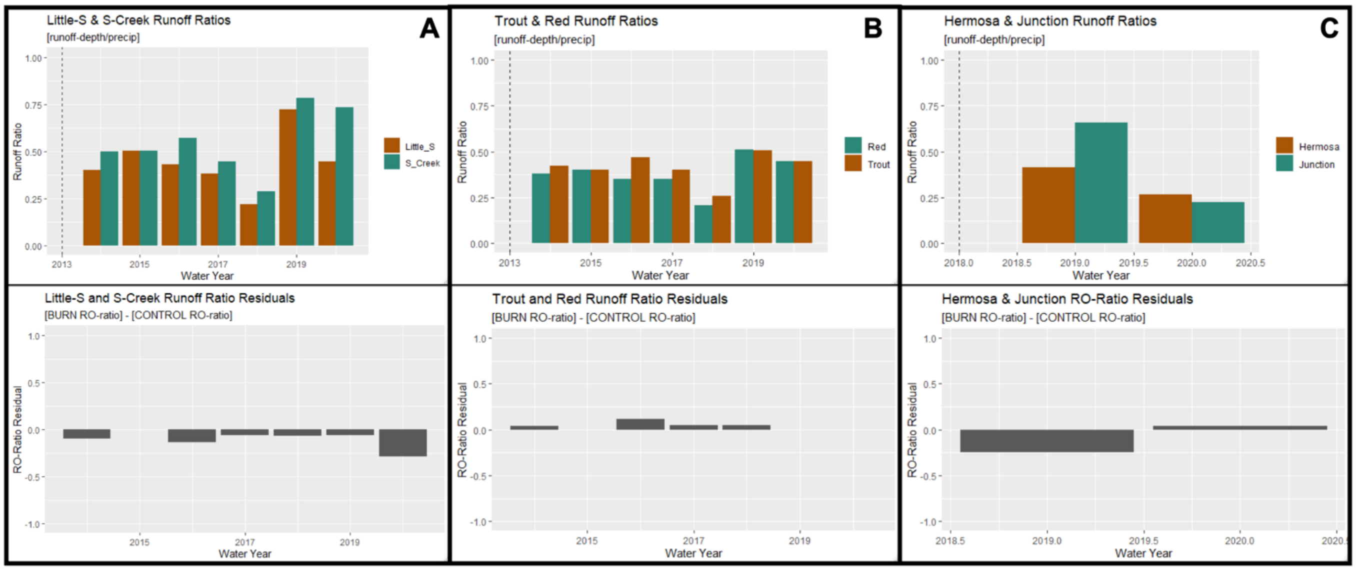

Figure 2: Runoff Ratios for Each PC System (top row) and Runoff Ratio "Residuals" (bottom row). *Top: A) LS-system RO-ratios, B) Trout-system RO-ratios, C) Hermosa-system RO-ratios. Veritcal dashed lines indicate the fire year. Burned catchments plotted in orange, control catchments in green. Bottom: RO-ratio residuals are computed using [RO-ratio$_{burn}$ minus RO-ratio$_{control}$].*

4.1.2 Residual Trends

Another way to account for the influence of precipitation on streamflow is through residual trend analysis. Residual trend analysis reveals how much of a response (or dependent) variable is explained by an independent variable. We fitted a linear model against annual precipitation (independent) and annual discharge (dependent) and plotted the residuals in **Figure 3**. Positive residuals indicate an increase in discharge that is not explained by precipitation and negative residuals indicate a decrease in discharge that is not explained by precipitation.

With vegetation (and associated transpiration) compromised by fire, we hypothesized that a greater percentage of annual flow would be explained by precipitation in burned catchments (especially in the first 1-3 post fire years), resulting in smaller magnitude residuals. Indeed, for both West Fork Complex PC systems, burned catchment residuals are the smallest in the first three post-fire years (2014-2016) with the exception of 2018, which was a drought year. However, also during the first three post-fire years, the magnitudes of control catchment residuals are also relatively small, and in some cases, smaller than burned catchment residuals. Control and burned residuals generally follow the same trends (increase/decrease together), but are most dissimilar second or third post-fire year (2015 in the LS-system and 2016 in the Trout-system).

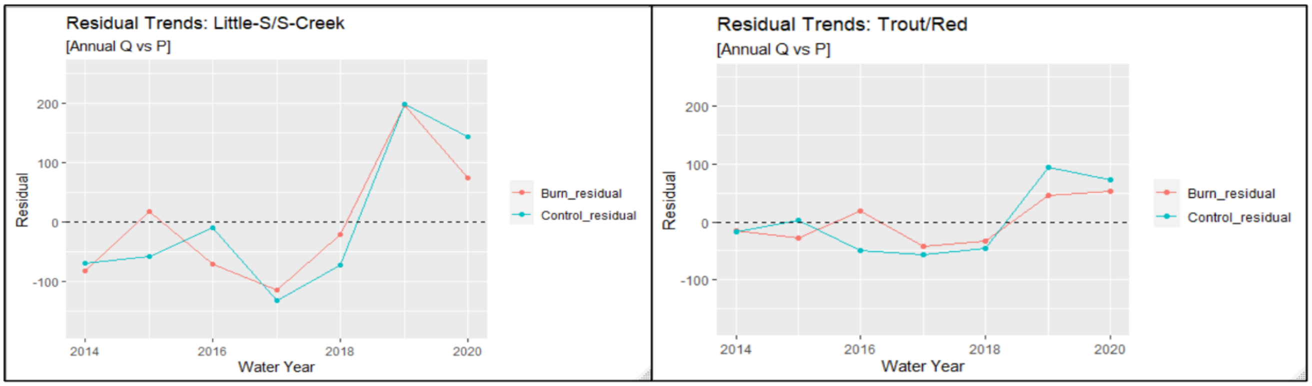

Figure 3: Residual Trends from the Linear Relationship between Annual Precipitation and Annual Discharge. *Red lines represent burned catchments and blue lines represent control catchments. Results from the Hermosa-system not shown, due to limited annual post-fire data.*

4.1.3 Timing of Annual Runoff

The timing (day of water year) of annual streamflow quartiles and annual flow durations were computed for each study basin. Streamflow centers of mass (COM) were broken down into quartiles representing the date that 25%, 50% and 75% of annual flow volume occurred each water year (Q25, Q50 and Q75, respectively). Annual flow duration was computed using the difference between Q75 and Q25, to reveal the time it took for the majority of annual streamflow to occur. Annual streamflow COMs and durations are shown in **Figure 4**.

Due to suspected post-fire reductions in infiltration pathways, we hypothesized that burned catchments would behave “flashier” than controls, especially in the first 1-3 post-fire years. Theoretically, this behavior would result in earlier annual runoff timing and shorter runoff durations in burned catchments. In both West Fork Complex PC systems, burned Q50 is slightly earlier than control Q50 in the first 2-3 post-fire years, while Q25 and Q75 are more-variable between burn and control catchments. In the LS-system burn flow duration is shorter than control flow duration for the first four post fire years. However, in the Trout-system, burn flow duration is longer than control flow duration for the first two post fire years. Otherwise, both control and burn COMs follow similar trends for Q25/Q50/Q75 and flow durations (increasing/decreasing together) with the most variability between control and burn occurring in the first 1-3 post-fire years.

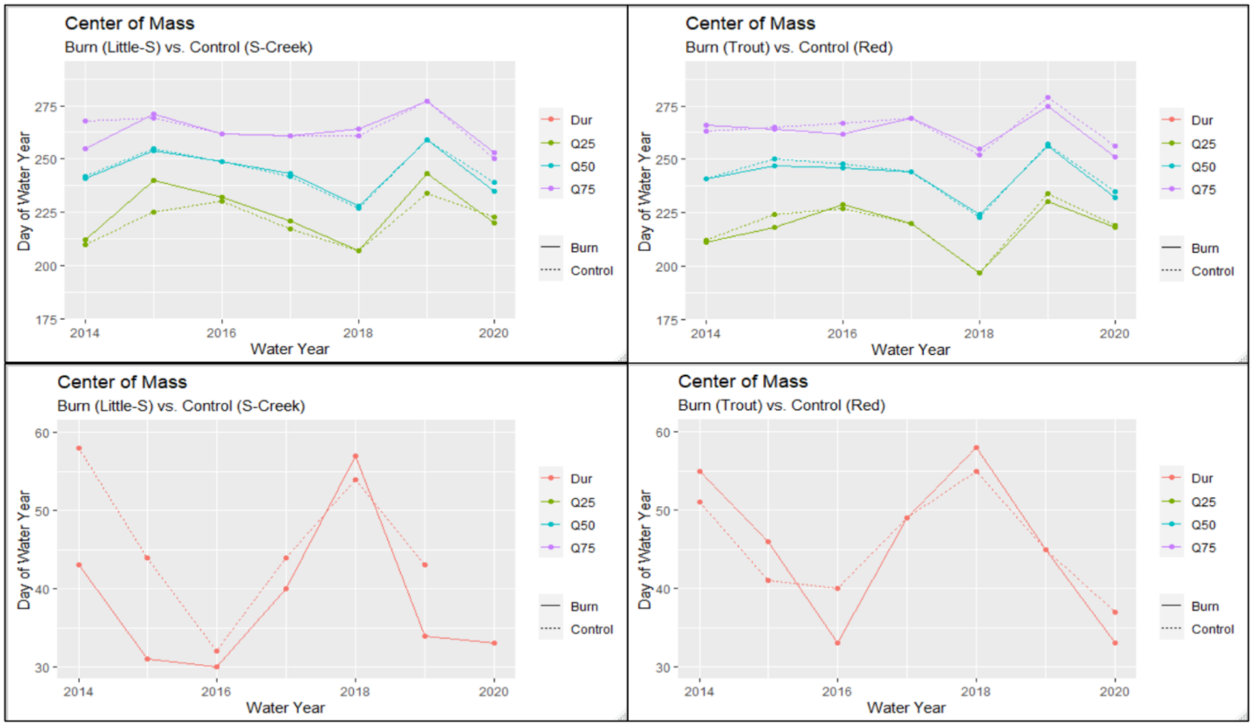

Figure 4: Annual Streamflow COM and Duration. *Burn catchments shown in as solid lines, control catchments as dotted lines. Left: LS-system. Right: Trout-system. Top: Streamflow COM shown as Q25 (green), Q50 (blue) and Q75 (purple). Bottom: Streamflow duration (orange). Results from the Hermosa-system not shown, due to limited annual post-fire data.*

4.2 Evapotranspiration Analysis

Like runoff ratios, evaporative fractions (EF) normalize annual AET against annual precipitation. **Figure 5** shows the EF (top) and EF ratio (bottom) for water years 2001-2020, where EF ratio is computed by $EF_{burn}/EF_{control}$. The purpose of the EF ratio is to normalize EF_{burn} against $EF_{control}$. Theoretically, EF should be <1, which is typically observed in the West Fork Complex catchments, with the exception of a few water years. Occasional instances where AET>P are generally unlikely and should only occur in rare circumstances where water leaves storage (ie: groundwater) to satisfy the eco-climatic demand for water. However, in the Hermosa-system, EF is consistently >1. While the Hermosa-system is located in a slightly more arid environment than the West Fork Complex catchments (based on aridity indices), the hydrologic mass balance between inputs (precipitation) and outputs (runoff and AET) does not allow for AET>P as a baseline condition. Here, we use SSEBop AET (based on relatively fine spatial resolution; 1km), which is likely over-representative of true AET conditions. Other AET products are being explored, but for now SSEBop based AET is presented, and we assume that while the magnitude is likely too high, the general trends (increases, decreases) are representative of true AET trends.

We hypothesized that burned EF would decrease relative to control EF, especially during the first 1-3 post-fire years. This behavior is observed in each PC system, with distinct burn/control trends in each. In the LS-system (**Figure 5-A**), burn and control EFs were generally similar pre-fire, then burn EF decreases relative to control post-fire. In the Trout-system (**Figure 5-B**), burn EF is generally higher than the control pre-fire, then after the fire, burned EF decreases and becomes more similar to control EF. In the Hermosa-system (**Figure 5-C**), burn EF is generally lower than the control pre-fire, then typically becomes even lower than the control during post-fire years.

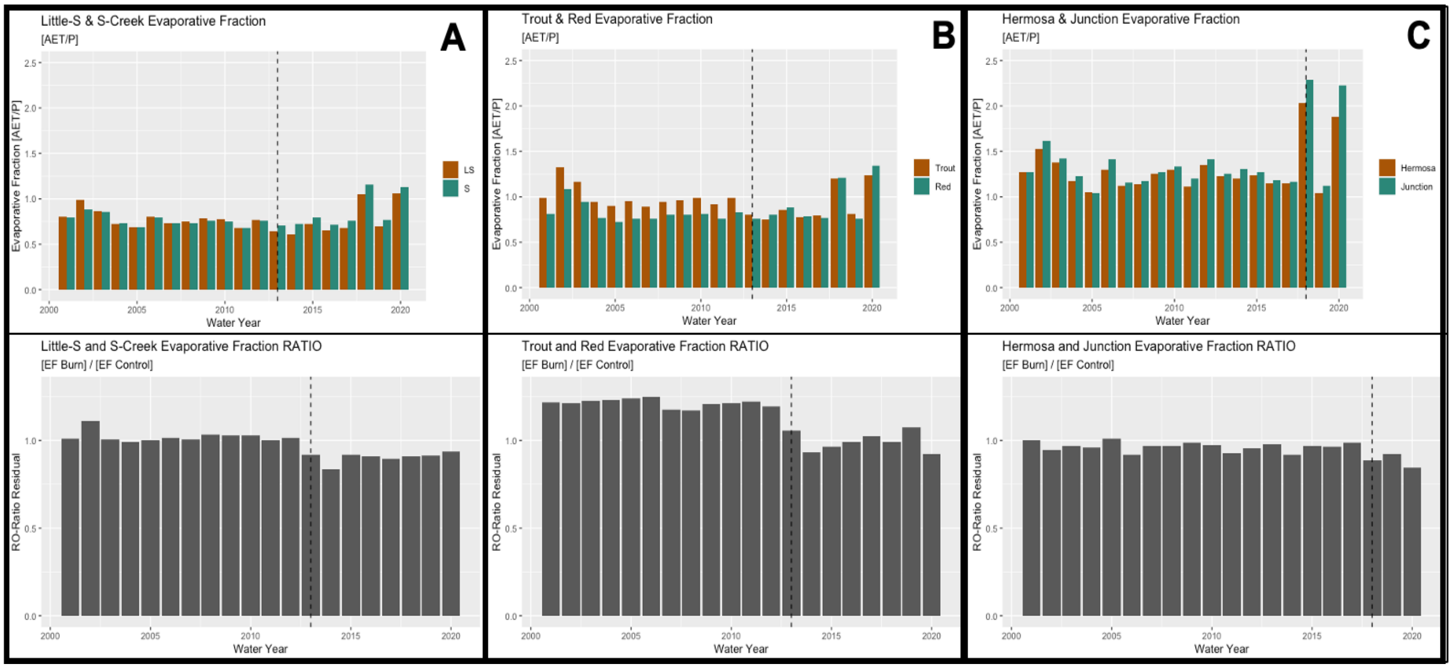

Figure 5: Evaporative Fractions and EF Ratios. *Vertical dashed lines indicate the fire year. A) LS-system, B) Trout-system, C) Hermosa-system. Top: Evaporative fractions; burned catchments plotted in orange, control catchments in green. Bottom: EF ratios.*

4.3 Leaf Area Index

Monthly leaf area index residuals ($LAI_{residual} = LAI_{control} – LAI_{burn}$) were computed for each PC system (**Figure 6**), to determine if LAI adequately captures the destruction in vegetation caused by wildfire. For each PC system, significant changepoints were detected (>98% confidence interval) during the water years of wildfire events. Specifically, changepoints were detected for the LS, Trout and Hermosa systems at [November 2012], [June 2013], and [June 2015, June 2018], respectively. The differences in pre- and post-changepoint $LAI_{residual}$ means are 1.26 (LS-system), 1.43 (Trout-system) and 2.20 (Hermosa-system). While not detected by changepoint analysis, the Trout-system exhibits a notable decline in $LAI_{residual}$ in the years leading up the fire (~2010-2013), which is likely related to pre-fire insect-induced vegetation. mortality. A similar trend is notable for the Hermosa system for the years ~2015-2018 (detected by a significant changepoint) and is also likely explained by insect mortality.

LAI results for the West Fork Complex sites generally agree with the contrast in NLCD-based land cover taken before (NLCD 2011) and after (NLCD 2016) the fire. Between 2011 and 2016, the Trout basin and Little-S basins experienced ~36% and ~21% reductions in evergreen forest (respectively), and were replaced almost exclusively with 'grassland/herbaceous' land cover. Based on these findings, we believe that LAI is a viable vegetation metric to incorporate into future modelling work (Objective 2).

4.4 General Discussion

We hypothesized that burned basins would produce more runoff, and be more flashy (and earlier) than control basins, especially in the first three post-fire years. None of the PCs evaluated in this study exhibited a pronounced difference in runoff volume in the first three post-fire years. The Trout-system was the only PC to experience greater runoff in the burned basin, while the LS-system experienced a decrease and the Hermosa-system was variable (**Figure 2**). However, the amount of runoff explained by precipitation was most variable between control and burned catchments in the first three post-fire years (**Figure 3**). Similarly, the variability in timing and duration of annual streamflow was also the most variable in the first three post-fire years; where the burned basins in the LS-system experienced shorter annual flow durations and in the Trout-system experienced slightly longer annual flow durations (**Figure 4**).

In the West Fork Complex sites, the extent and severity of wildfire is very similar between both paired catchment systems (**Table 1**), so the disagreement in post-fire runoff trends between LS and Trout-systems is not intuitive and requires further exploration. First, the extent and severity of destruction caused by wildfire *alone* was likely not enough to produce significant change in the timing and magnitude post-fire runoff. However, in the Trout-System, where insect mortality was more-severe (especially in the burned catchment), the *compounded impact* of both wildfire and insect mortality may have been enough to produce an increase in post-fire runoff. This idea is supported by both changes in evaporative fraction (**Figure 5**) and $LAI_{residual}$ (**Figure 6**), which indicate that greater changes to AET and vegetation density occurred in the Trout-System than in the LS-system (despite the extents and severities of burn being nearly identical).

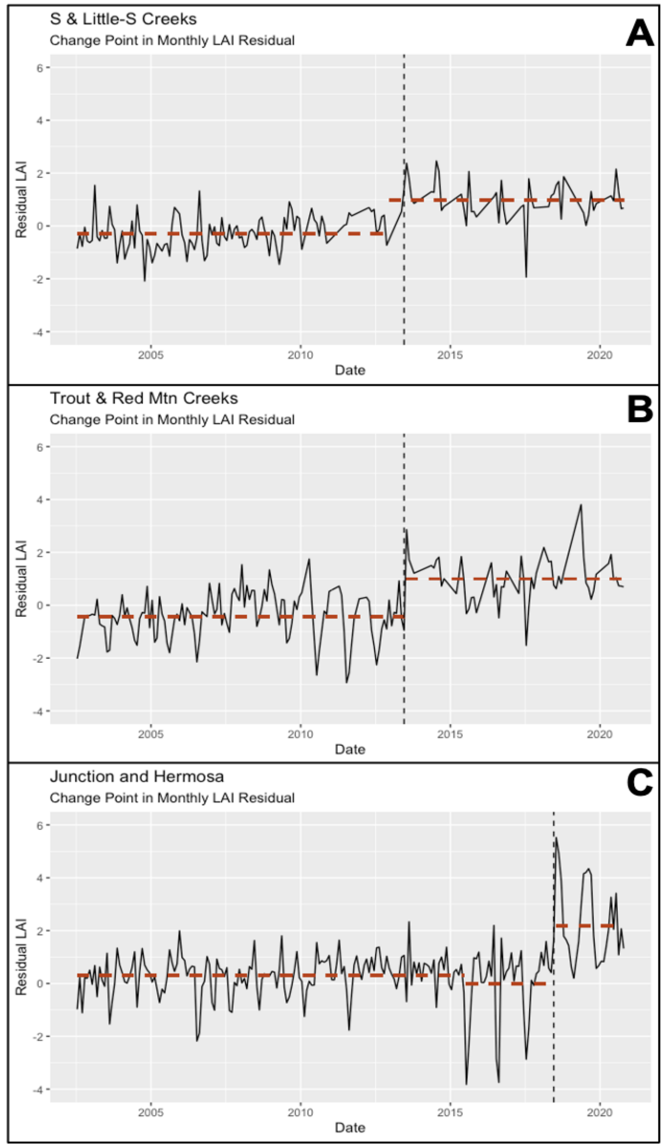

Figure 6: Leaf Area Index Residuals [$LAI_{control}$ – LAI_{burn}]. *A) LS-system, B) Trout-system, C) Hermosa-system. Vertical black dashed lines indicate the fire year. Bold orange horizontal lines plot mean LAI before and after each significant changepoint.*

The most significant takeaway from this work is the necessity of considering co-occurring disturbances. A common practice in disturbance hydrology is to focus on the hydrologic response to a single disturbance, and assuming that the disturbance in question is isolated in space and time from other disturbance signals. However, our findings, while constrained to a small study area, reveal that this assumption is seriously limiting. This is particularly true for post-fire hydrologic analyses, because wildfires often occur in landscapes that have been impacted by insect mortality or other forest disease (Parker et al., 2006). And while insect mortality is typically widespread, the occurrence is likely spatially and temporally heterogeneous (and consequently difficult to quantify or even qualify). Along those lines, the variability in post-fire streamflow seen in the literature (Goeking & Tarboton, 2020), and especially in the southern Rocky Mountains (Saxe et al., 2018), is likely driven in some part by the widespread occurrence of insect mortality in fire-prone regions. Thus, better spatially and temporally quantitative representations of forest mortality are needed to better characterize the extent to which forest mortality influences hydrology. Finally, a major limitation of the paired catchment approach to disturbance hydrology, is the (often) lack of pre-disturbance information. In this study, satellite based AET and LAI were available for both pre- and post-fire time periods, but runoff data was limited to only the post-fire period. In instances when pre-fire information is not available, comparisons are limited to the relationship between control and impact sites and leaves the question: "*Was the pre-disturbance relationship different than the post-disturbance relationship between control and impact?*" We have the most confidence in results that juxtapose pre- and post-fire information with control and impact site observations.

5. Conclusion

This study evaluates the hydrologic response to wildfire and insect induced forest mortality for three snow dominated paired catchment systems in Colorado's San Juan Mountains. A close evaluation of surface water budget components (precipitation, runoff and AET) revealed that the impact of fire alone was likely not great enough to produce increases in runoff in burned basins, but that the combined impact of fire and insect mortality may alter evapotranspiration enough to tip the scale toward incased post-fire runoff generation. Water managers and research hydrologists who seek to understand how wildfires impact water yield and timing, should also consider co-occurring disturbances (especially widespread disturbances like forest mortality) that may exacerbate the hydrologic response to wildfire.

The water budget analysis described here (Objective 1) sets the stage for ongoing work, where Leaf Area Index is being integrated into a water balance model to quantitatively represent forest-disturbance within the model (Objective 2) and to then utilized to evaluate future forest-disturbance scenarios (Objective 3).

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

- **Completed:**
    - Schneider, K.E., Rust, A.J., Randell, J., Hogue, T.S. *Modelling Post-Fire Hydrologic Recovery in Snow Dominated Catchments in Colorado's San Juan Mountains*. American Geophysical Union. December 2020. Virtual conference (oral presentation).
    - Schneider, K.E. *Advancing the Capability of Hydrologic Models in Poorly Monitored Domains and Disturbed Catchments*. PhD Dissertation Proposal. Submitted to the dissertation committee November 27, 2020.
- **Planned:**
    - Schneider, K.E. Rust, A.J, Hogue, T.S. *Post-fire water budget analysis for snow dominated paired catchment systems in Colorado's San Juan Mountains*. (in-prep).
        - Will also contribute to the student investigators second dissertation chapter
    - Schneider, K.E. Rust, A.J, Hogue, T.S. *Representing disturbance induced land cover change in hydrologic models using remote sensing products* (planned for completion in September 2021).
        - Will also contribute to the student investigators third dissertation chapter

Appendix C: Metadata

Data collected during this project includes surface water budget components and remotely sensed vegetation information: streamflow (collected in the field), precipitation (sourced from PRISM rasters), evapotranspiration (currently sourced from SSEBop rasters, but will likely be sourced elsewhere for future analyses) and LAI (MODIS). All data sourced from gridded products was extracted and area-weighted to study basin polygons. Resulting data will be stored in comma-delimited ASCII text files and will include monthly timeseries of the water budget and vegetation components previously listed. These data will be archived with the Forest Service Research Data Archive along with associated metadata. A metadata draft has also been uploaded to the JFSP website under the final report tab.

Deviations from original data management plan:

- Precipitation and temperature information was sourced from PRISM (rather than SNOTEL sites, as listed in the original data management plan) due to better spatial representation of complex terrain. PRISM data for the pixels containing SNOTEL sites were compared against actual in-situ SNOTEL observations and showed strong agreement.

- Evapotranspiration was sourced from SSEBop (as indicated in the original data management plan), however SSEBop appears to overestimate ET in the San Juan region. So, moving forward, we will likely source ET from the remotely sensed MODIS (MOD16-A2) product.
- Soil moisture was not sourced for this work. Instead, we will compute changes in storage (‘delta S’) as a residual of water budget inputs and outputs to represent total storage in our systems.
- Vegetation data was sourced from a MODIS-based Leaf Area Index (LAI) product, rather than from NDVI or EVI (as listed in the original data management plan). We opted to use LAI, rather than NDVI/EVI, because LAI provides a better quantitative metric for vegetation coverage, whereas NDVI/EVI is more qualitative.